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An Improved Telescope Triple Object-Glass.

By J. William Gifford. (Plate 7.)

(*Communicated by Sir David Gill, K.C.B.*).

The idea of employing three separate kinds of glass for the purpose of eliminating the secondary spectrum from the object-glasses of telescopes is not new. With the more limited choice of optical glass then possible, the problem was attacked successfully some thirty years ago by Sir Howard Grubb, Hastings, and Shroeder, and in more recent years by Abbe, Dennis Taylor, and Harting. Of the earlier workers, that of Hastings has come more immediately to my notice. Hastings draws attention (*Amer. Journ. Science and Arts*, vol. xviii., No. 108, p. 433) to the inaccurate measurements of the optical constants at his disposal, and attributes some anomalies in his results to this cause alone. Before proceeding further, it is my purpose to refer to a series of measurements of the optical constants of glasses which I have made for the purpose of comparison with those sent out by the makers, and from some of which the triple referred to and other lenses have been made.

The system adopted for making the measurements has already been described (*Roy. Soc. Proc.*, Feb. 13, 1902). Briefly, it is independent of measurements of angle. By means of a temperature refraction coefficient the indices are all brought to a temperature of 15° C., and by a new system of illumination greater accuracy in reading the goniometer circle is ensured. In all, 14 different glasses have been measured for the following wave-lengths:—

A′.	7682·45 (K$_{\alpha}$)	E.	5270·11 (Fe)
B′.	7065·59 (He)	F.	4861·49 (H$_{\beta}$)
C.	6563·04 (H$_{\alpha}$)	Φ.	4678·35 (Cd$_{6}$)
D.	5893·17 (Na)	G′.	4340·66 (H$_{\gamma}$)
Λ.	5607·1 (Pb)		

Seven of these have also been measured for wave-length H′ 3961·68 (Al), and the seven others for wave-lengths 4553·0 (Pt) 4415·0 (Cd).

By this we get a range of refractive indices for line D from 1·501118 (light Borosilicate crown) to 1·746410 (extra dense flint); and if the indices are placed in columns in ascending series by interpolating between corresponding elements in contiguous columns, it is easy to check any considerable errors in a glass whose optical position lies between those of the glasses to which the columns correspond.

It may be taken that all errors lower than the 5th. decimal place have been eliminated, and that in this place there are few greater than unity. The various lenses which have been calculated from these measurements, and since constructed by Hilger, have

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all come out as accurately in agreement with the calculations as mechanical limitations allow.

In the case of most of the glasses referred to, after a preliminary rough measurement with a single prism, a part or all of the melting was purchased. Then, choosing three blocks of glass from it at hazard, these were cut into prisms, and each measured for some central line in the spectrum. The mean index thus obtained was used as a control for the others, in much the same way as the temperature coefficient, the others being brought each to a proportionate index.

To show that my indices are reliable, I have dwelt at some length on these points. I now hope to show that a slight variation in the index has a great, and in the case of a triple a profound, influence on the correspondence between the calculations and the performance of the lens after construction.

I take first the case of a $3\frac{1}{4}$-in. aperture doublet constructed some two years since. The glasses used were a light Borosilicate crown with $V = 63·43$ and a dense flint with $V = 36·75$. Lines C, D, and F were used for obtaining the correction for achromatism, lines C and F being equalised as to focal length. The makers' measurements and my own for these lines follow :—

	Makers.	Gifford.
C.	1·50764	1·506254
D.	1·51000	1·508642
F.	1·51563	1·514265

Flint.

C.	1·60710	1·606899
D.	1·61180	1·611638
F.	1·62367	1·623449

The foci for achromatism for a focal length of unity were—

	Makers.	Gifford.
Crown	0·42155	0·42797
Flint	−0·72877	−0·71812

Taking now, for the purpose of calculating a triple, a Baryta light flint with $V = 50·25$, a Borosilicate flint with $V = 45·82$, and a Borosilicate crown with $V = 60·70$, and the same wave-lengths, we have for the refractive indices—

Baryta Light Flint.

	Makers.	Gifford.
C.	1·57117	1·571003
D.	1·57450	1·574329
F.	1·58261	1·582433

Borosilicate Flint.

	Makers.	Gifford.
C.	1·57164	1·572056
D.	1·57530	1·575742
F.	1·58418	1·584621

Borosilicate Crown.

	Makers.	Gifford.
C.	1·49875	1·498675
D.	1·50117	1·501118
F.	1·50700	1·506930

Passing over the tedious sum (shown in the Appendix for lines B′, Λ and Φ), the resulting foci for unity were—

	Makers.	Gifford.
Baryta lt. ft.	0·37887	0·32402
Boro. ft.	−0·17443	−0·20618
Crown	0·24429	0·36179

It will be noted that my indices are taken to 6 places.* Now if we take these indices to 5 places only, the foci are as follows:—

Baryta Lt. ft. 0·31857, Boro ft. −0·21204, Boro crown 0·38805; and if we take them to 4 places only, then two of the foci become minus quantities.

All this goes to show how very sensitive the corrections of a triple for colour are to slight variations of refractive index, and why earlier constructors relied almost implicitly on figuring.

For the construction of the triple referred to in this paper, a 3-in. of 37·5-in. focus, the three above-mentioned glasses were taken, but instead of the usual corrections (lines B, D, and G being equalised), those chosen for the purpose were, lines B′7066·59, Λ5607·1, and Φ 4678·35. B′ is the brick-red line of helium, and is very near B.

Λ is a prominent lead line and occupies the position of maximum visual effect in the spectrum lying between D and E.

Φ is a cadmium line, and is near wave-length 4604 (Li), which has been mentioned by Sir W. Abney as the average point of maximum photographic effect for rays which have passed through any thickness of glass. As the Borosilicate flint is tinged with yellow, I have placed this point slightly lower.

Besides the evident advantage of using both Λ and this cadmium line, it was found that the use of Φ resulted in longer radii than if G or G′ were used, so that we are free from all the inherent difficulties of steep curves. Hastings lays down the point that no radius should be shorter than 1/15 of the focal length. This means that the curvature sums must not exceed 30 for a focus of 1.

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* All the indices were observed to 7 places.

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The following examples show the effect of using Φ instead of G′ (Hγ), and that the curvature sums are well within Hastings' requirements. Calling these curvature sums, with Hastings, A, B, and C, we have, with the lines for correction as shown,

B′, A and G′

$A = 11{\cdot}31376.$ $B = -12{\cdot}45968.$ $C = 3{\cdot}34342.$

B′, A and Φ

$A = 8{\cdot}94155.$ $B = -11{\cdot}01247.$ $C = 4{\cdot}39960.$

From these curvature sums the reciprocals of the foci were found. These reciprocals are really the angles made with the axis by each of the elements of the triple when the incident ray parallel to the axis is at such a height from the vertex that the emergent ray from the last surface makes one second of arc only with the axis, as described by Steinheil and Voit (*Handbuch der angewandten Optik*, p. 69), thus—

$$\frac{1}{f} = A(\mu - 1). \qquad \frac{1}{f'} = B(\mu' - 1). \qquad \frac{1}{f''} = C(\mu'' - 1).$$

A trigonometrical trace was then made for such a height, inserting these angles, and finding the corresponding radii at each surface. The difference at such a height between sine and arc is negligible (*loc. cit.*). From the final traces a diagram has been constructed for a lens of 19 metres focal length and a curve drawn. A similar curve for a doublet of the same focal length has also been drawn for comparison. It will be noted that the triple is almost independent of the wave-length.

With the radii and thickness found in this way the lens was then constructed, rigid adherence having been observed to the data given, without any attempt at improvement by figuring.

It was found, after squaring on, that although the definition was fair, a small amount of negative spherical aberration was present.

By separating the last two surfaces a few thousandths of an inch this disappeared, and a line test, such that at 608·7 yds. the angle subtended by the interval between any two of the lines was $1''{\cdot}52$ of arc, was resolved at 600 yds.

This is equivalent to a resolving limit of $\frac{4''{\cdot}55}{a}$.

It will be seen by this that the definition of this triple O.G of 3-in. aperture is excellent. The calculation for the final correction of colour having been made for rays incident at the extreme edge, any residual error is extremely difficult to detect with even high powers.

Mr. Nelson, on several occasions President of the R. Micro. Soc., to whom I should like to say I am indebted for all my

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earlier teaching in optics and the trigononometrical trace of a ray, undertook the line test.

The actual radii and the thickness of the triple constructed are given in the Appendix, and also a worked-out example of the foci (thin lens) by a short formula which has been condensed from Coddington by Mrs. Gifford.

Before closing this paper, I should like to thank Sir David Gill (to whom my bringing this forward is entirely due) for his great kindness; Messrs. Chance Bros., Messrs. Schott of Jena, and Messrs. Mantois of Paris, for the facilities they have afforded me for measuring their glasses; and last, but not least, Mr. F. Twyman, of Messrs. Hilger Ltd., for the rare skill he has shown in accurately following the optical data given.

APPENDIX.

Reciprocals of Foci for Apochromatic Triple.

μ is baryta light flint. μ' is borosilicate flint. μ'' is borosilicate crown.

Differences of Proportional Spectra.

A′—D.	D—F.	F—G′.
0·00168	−0·00030	0·00805

Refractive Indices.

B′.7066(He).	A.5607(Pb).	Φ.4678(Cd₆).
$\mu_1 = 1{\cdot}569074$	$\mu_2 = 1{\cdot}576104$	$\mu_3 = 1{\cdot}584492$
$\mu'_1 = 1{\cdot}569909$	$\mu'_2 = 1{\cdot}577675$	$\mu'_3 = 1{\cdot}586869$
$\mu''_1 = 1{\cdot}497250$	$\mu''_2 = 1{\cdot}502400$	$\mu''_3 = 1{\cdot}508365$

$$A = \{(\mu_3 - \mu_2)(\mu'_2 - \mu'_1) - (\mu'_3 - \mu'_2)(\mu_2 - \mu_1)\}(\mu''_2 - 1) = 0{\cdot}0000002549117.$$

$$B = \{(\mu''_3 - \mu''_2)(\mu_2 - \mu_1) - (\mu_3 - \mu_2)(\mu''_2 - \mu''_1)\}(\mu'_2 - 1) = -0{\cdot}0000007303256.$$

$$C = \{(\mu'_3 - \mu'_2)(\mu''_2 - \mu''_1) - (\mu''_3 - \mu''_2)(\mu'_2 - \mu'_1)\}(\mu_2 - 1) = 0{\cdot}0000005904547.$$

$$F = 1.$$

$$\frac{1}{f} = \frac{C}{A+B+C} = 5{\cdot}132568. \quad \frac{1}{f'} = \frac{B}{A+B+C} = -6{\cdot}348405.$$

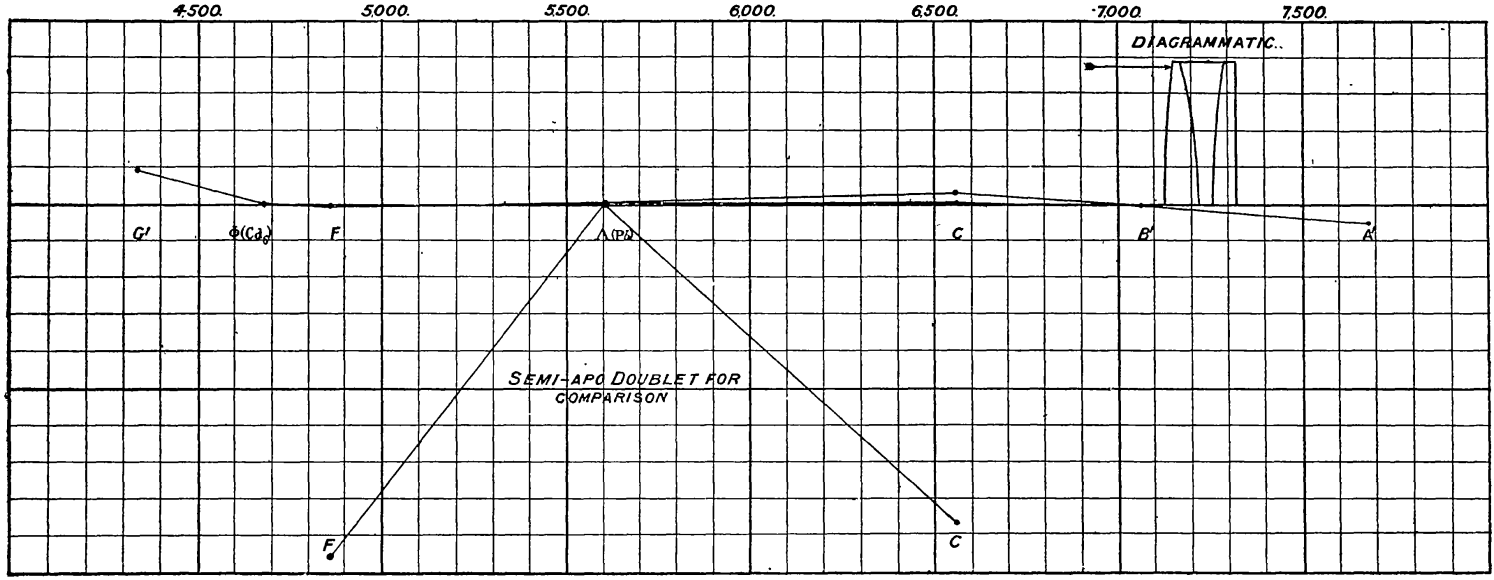
$$\frac{1}{f''} = \frac{A}{A+B+C} = 2{\cdot}215837.$$

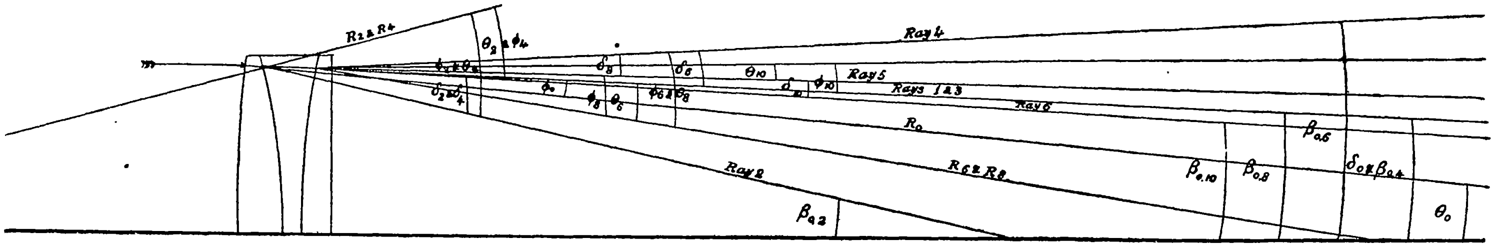
$$\frac{1}{f} + \frac{1}{f'} + \frac{1}{f''} = 1. \quad f' = -0{\cdot}157519.$$

$$\text{Corresponding curvature sum} = \frac{\frac{1}{f'}}{\mu'_2 - 1} = -10{\cdot}989579.$$

CURVE OF FOCAL LENGTHS AND WAVE-LENGTHS.

For the purposes of the curve, the data given have been multiplied by twenty. For comparison, the doublet already referred to has been treated similarly. All the focal lengths are from trigonometrical traces for edge rays, not for axial rays.





TRIGONOMETRICAL TRACE.